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Improving efficiency of supercontinuum generation in photonic crystal fibers by direct degenerate four-wave-mixing

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Abstract: The efficiency of supercontinuum generation in photonic crystal fibers is significantly improved by designing the dispersion to allow widely separated spectral lines generated by degenerate four-wave-mixing directly from the pump to broaden and merge.

Introduction.

Photonic crystal fibers (PCFs) [1] and tapered fibers [2] are promising sources for efficient supercontinuum generation (SCG) due to their unusual dispersion properties and high effective nonlinearities. These fibers have similar dispersion and nonlinearity characteristics and they have the advantage that their dispersion may be modified by a proper design of the cladding structure [3], and by changing the degree of tapering [2], respectively. Using femtosecond pulses a supercontinuum (SC) spanning one octave has been generated in a PCF, whereas impressive two octave SC has been obtained in a tapered fiber. The latter two octave wide SC was later explained to be a result of self-phase modulation (SPM) and direct degenerate four-wave-mixing (FWM) [4].

However complex high power femtosecond lasers are not necessary, - SCG may be achieved with picosecond and even nanosecond pulses. Thus Coen *et al.* generated a one octave SC in a PCF using sub-kilowatt picosecond pulses and showed that the primary mechanism was the combined effect of stimulated Raman scattering (SRS) and parametric FWM, allowing the Raman shifted components to interact efficiently with the pump [5]. Here we show how direct degenerate FWM can be used to significantly improve the efficiency of SCG with sub-kilowatt picosecond pulses in PCFs, if the dispersion is properly designed.

Improving efficiency of SCG with picosecond pulses in PCFs using degenerate FWM.

We study the SCG process numerically using the well known coupled nonlinear Schrödinger equations that describe the evolution of the x- and y-polarization components of the field for pulses with a spectral width up to 1/3 of the pump frequency [5]. This model accounts for SPM, cross-phase-modulation, FWM, and SRS. An initial random phase noise seeding of one photon per mode is included.

We consider the same PCF and numerical and experimental data as in [5], kindly provided by S. Coen. Thus we pump along the slow axis with 30ps

pulses of $I_p=400\text{W}$ peak power and pump wavelength $\lambda_p=647\text{nm}$. Our PCF has core area $A_{\text{core}}=1.94\mu\text{m}^2$, dispersion $D(\lambda_p)=-30\text{ps}/(\text{nm}\cdot\text{km})$, zero dispersion wavelength $\lambda_{z1}=675\text{nm}$, $n_2=3\times 10^{-20}\text{m}^2/\text{W}$, and birefringence $n_x-n_y=1.9\times 10^{-6}$. The dispersion is expanded around the pump to include $\beta_2=7.0\text{ps}^2/\text{km}$, $\beta_3=5.1\times 10^2\text{ps}^3/\text{km}$, $\beta_4=-4.9\times 10^5\text{ps}^4/\text{km}$, $\beta_5=1.2\times 10^7\text{ps}^5/\text{km}$, $\beta_6=-1.8\times 10^{10}\text{ps}^6/\text{km}$, and $\beta_7=1.2\times 10^{13}\text{ps}^7/\text{km}$. A uniform loss of 0.1dB/m is used and the effective area is approximated with the core area, giving the nonlinearity parameter $\gamma=2\pi n_2/(\lambda_p A_{\text{core}})=0.15(\text{Wm})^{-1}$.

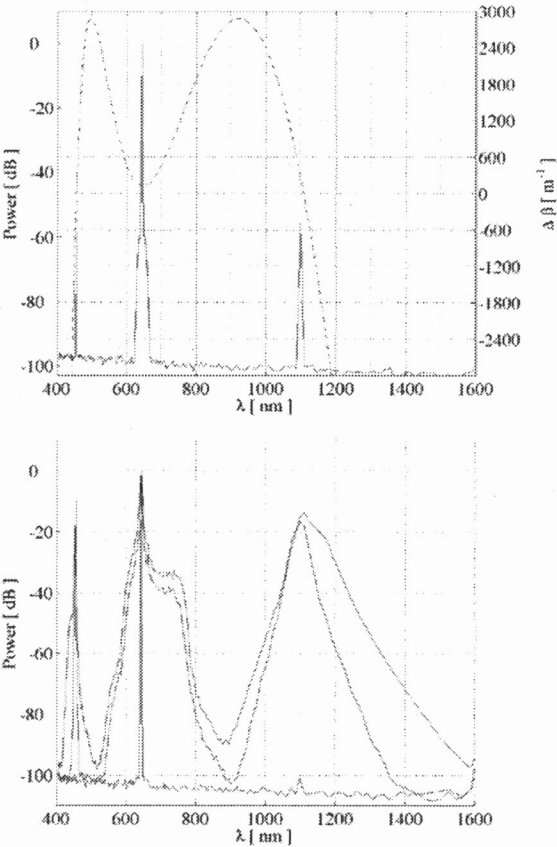


Fig.1 a) Phase-mismatch $\Delta\beta$ and spectrum of the slow axis polarization component at $L=17.4\text{cm}$. b) Same spectrum at $L=4.3\text{cm}$, 2.6m , and 3.7m .

We use the standard split-step Fourier method with 2^{17} points in a time window of $T=236\text{ps}$. In our longest

simulation out to $L=3.7\text{m}$ the photon number is conserved to within 5% of its initial value. Due to our large spectral window (405nm \rightarrow 1613nm) we see in Fig.1(a) the emergence of FWM stokes and anti-stokes waves at the wavelengths $\lambda_s=1100\text{nm}$ and $\lambda_{as}=458\text{nm}$ for which the phase matching condition $\Delta\beta=\beta_s+\beta_{as}-2\beta_p+\gamma_p=0$ is satisfied. The spectral window presented in [5] was narrower and thus λ_s and λ_{as} were not observed. We find the maximum FWM parametric gain to be twice the maximum SRS gain, which explains why the FWM stokes and anti-stokes components appear before the SRS components.

The loss and walk-off of the PCF gives the maximum distance L_{max} over which nonlinear processes, and thus the SCG process, are efficient. From Fig.1(b) we see that after the FWM stokes and anti-stokes components are generated they broaden much in the same way as the central part of the spectrum around the pump. The merging of the spectral parts around λ_{as} , λ_p , and λ_s would create an ultra broad spectrum as observed in tapered fibers with femtosecond pulses [2,4]. However, in this particular case the FWM stokes and anti-stokes lines are too far away for a merging to take place within the maximum length L_{max} , i.e., before nonlinear effects become negligible.

The wavelengths λ_s and λ_{as} can be adjusted to be closer to the pump wavelength λ_p by a proper design of the dispersion. This will enable the FWM stokes and anti-stokes lines to broaden enough to allow a final merging. To show the effect we modify β_2 , β_4 , and β_6 to $\beta_2=1.0\text{ps}^2/\text{km}$, $\beta_4=-2.5\times 10^5\text{ps}^4/\text{km}$, and $\beta_6=-3.25\times 10^{10}\text{ps}^6/\text{km}$. The phase-matching condition $\Delta\beta=0$ then gives $\lambda_s=850\text{nm}$ and $\lambda_{as}=530\text{nm}$. The effect on the dispersion profile is to down-shift the zero dispersion wavelength to $\lambda_p=660\text{nm}$ and reduce the normal dispersion to $D(\lambda_p)=-4.35\text{ps}/(\text{nm}\cdot\text{km})$, as shown in Fig.2.

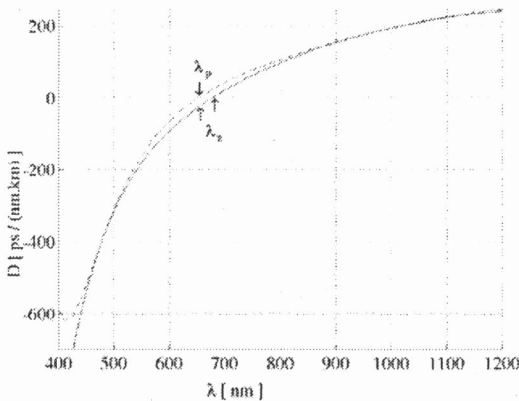


Fig.2 Original dispersion [5] (solid line) and our modified dispersion (dashed line).

The numerical results shown in Fig.3 confirm our hypothesis. The FWM stokes and anti-stokes lines

are still widely separated, but now generated close enough to the pump to broaden and merge. The resulting ultrabroad SC is flat within 20dB and spans 510nm (at -40dB from the flat part) in contrast to the original 230nm observed in [5].

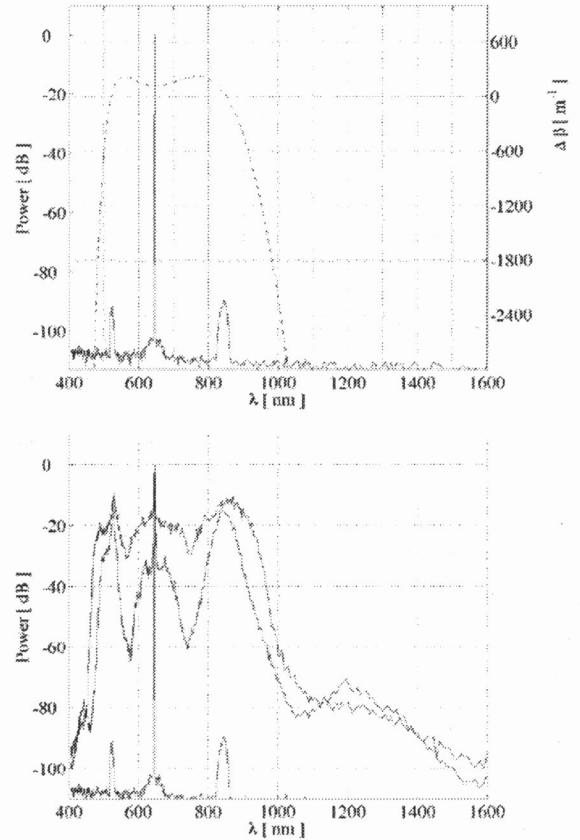


Fig.3 a) Phase-mismatch $\Delta\beta$ and spectrum of the slow axis polarization component at $L=17.4\text{cm}$. b) Same spectrum at $L=8.7\text{cm}$, 43cm , and 2.154m .

Conclusion:

We have numerically considered SCG in birefringent PCFs using sub-kilowatt picosecond pulses. Our results show that by properly designing the dispersion properties and using the simultaneous broadening and final merging of widely separated pump and FWM stokes and anti-stokes lines the SCG efficiency can be significantly improved. Further investigations will involve the robustness of the process towards variations in the birefringence along the PCF. This work was supported by the Danish Technical Research Council (Grant no. 26-00-0355) and the Graduate School in Nonlinear Science (The Danish Research Agency).

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